The radio-luminosity – black hole mass correlation for quasars from the FIRST Bright Quasar Survey, and a "unification scheme" for radio-loud and radio-quiet quasars.

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ABSTRACT

Several independent lines of evidence now point to a correlation between black hole mass, $M_{\rm bh}$, and radio-luminosity. In this paper we discuss the correlation for quasars from the FIRST Bright Quasar Survey (FBQS), using black hole mass estimates from Hβ linewidths. The FBQS objects fill in the gap between the radio-loud and radio-quiet quasars in the radio-luminosity – optical-luminosity plane, and we find that they fill the corresponding gap in the $M_{\rm bh}$ – radio luminosity correlation. There is thus a continuous variation of radio luminosity with $M_{\rm bh}$, and no evidence for a "switch" at some set of critical parameter values which turns on powerful radio jets. By combining the FBQS data with that for quasars from the Palomar-Green survey we find evidence for a dependence of radio-luminosity on accretion rate relative to the Eddington limit, $L/L_{\rm Edd}$, as well as on $M_{\rm bh}$, consistent with the well-known radio-optical correlation for radio-loud quasars. We therefore suggest a new scheme to "unify" radio-loud and radio-quiet objects in which radio luminosity scales $\propto M_{\rm bh}^{1.9\pm0.2}(L/L_{\rm Edd})^{1.0}$ for $L/L_{\rm Edd} \sim 0.1$, with an apparently weaker accretion rate dependence at low $L/L_{\rm Edd}$. The scatter about this relation is ±1.1 dex, and may well hide significant contributions from other physical effects, such as black hole spin and radio source environment.

Subject headings: quasars: general – radio continuum: galaxies – galaxies: active

1. Introduction

Evidence for a link between black hole mass and radio-loudness in quasars has been accumulating for the past decade (see Laor 2000), but recently several new pieces of evidence have come to light. The host galaxy properties suggest a link; nearly all radio-loud quasars and radio galaxies are hosted by giant ellipticals, whereas radio-quiet quasars can exist in spirals (Bahcall et al. 1997; McLure et al. 1999). Coupled with the correlation of black hole mass and bulge mass seen in nearby galaxies (e.g. Magorrian et al. 1997), this implies that the radio-loud quasars and radio galaxies are likely to be hosted by objects with the most massive black holes (McLure et al. 1999). Although controversial, it seems that the fraction of radio-loud quasars does increase with optical luminosity [Hooper et al. 1995; Goldschmidt et al. (1999); Impey & Petry (2000); but see Stern (2000) for a dissenting view], again consistent with the idea that the most massive black holes are more likely to produce powerful radio sources (Lacy, Ridgway & Trentham 2000). The energy stored in giant radio lobes is $\gtrsim 5\times10^{5}M_{\odot}c^{2}$; assuming a plausible efficiency of conversion, this implies a black hole mass $\gtrsim 10^{7}M_{\odot}$ (Rawlings & Saunders 1991). Most recently, Laor (2000) estimated black hole masses for $z<0.5$ quasars in the optically-selected Palomar-

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Green (PG) Survey of Green, Schmidt & Liebert (1986), using black hole masses derived from the linewidths of broad Hβ and an estimate of the size of the broad-line region. He found a significant difference in the distributions of black hole masses for radio-loud and radio-quiet quasars, with radio-loud quasars generally having more massive black holes. A correlation between radio luminosity and black hole masses also estimated from linewidths, but using the narrow [OIII]5007 line, was found by Nelson (2000). His correlation only worked for radio-quiet quasars, however, perhaps because radio-loud quasars tend to have a larger amount of very extended (~ 30 kpc scale) [OIII] emission (Stockton & MacKenty 1987).

In this paper we discuss the black hole mass – radio-luminosity correlation with particular reference to quasars in the FIRST Bright Quasar Survey (FBQS; Gregg et al. 1996; White et al. 2000). The unique radio-optical selection criteria of this survey make it particularly sensitive to quasars with radio luminosities between the traditional radio-loud and radio-quiet classes. It is thus ideal for a quantitative investigation of the correlation of black hole mass and radio-loudness. We follow Laor (2000) in using estimates of black hole masses based on Hβ linewidths. McLure & Dunlop (2000) show that black holes masses derived in this way follow the same correlation of black hole mass with host bulge luminosity as those derived from stellar dynamics, so are probably reasonably accurate.

We assume a cosmology with $H_0 = 50\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ and $\Omega = 1$, $\Lambda = 0$ throughout.

2. The FBQS sample

The FBQS consists of optically unresolved, bright ($R \leq$17.8 mag), blue ($B - R \leq$2.0) quasars selected from the FIRST radio survey (Becker, White & Helfand 1995). At the time of the radio observations used herein, the survey consisted of 607 quasars, 80% of which were previously unknown. The sample used here is over 90% complete and differs from the full FBQS sample in two ways: we limited the range of redshifts to be $0.3 < z < 0.5$ and also only used sources with $M_B < -23$. The upper redshift limit ensures that Hβ is present in the spectrum. The absolute magnitude limit ensures that contamination of the image by host galaxy light is small [the host galaxies observed by Bahcall et al. (1997) all have $M_B \gtrsim -22.5$]. $M_B \approx -23$ corresponds to our optical selection limit at $z \sim 0.3$, so we have excluded lower redshift objects from the sample to minimize the number of objects where host galaxy light can contribute significantly to M_B. The absolute magnitude limit also ensures that our sample should be free of any significant biases due to exclusion of objects through the FBQS selection criteria, which requires the image to be stellar on at least one of the Palomar Observatory Sky Survey plates. This selection results in a sample of 60 FBQS objects.

The sources were observed at 20 and 3.6 cm (to obtain simultaneous radio spectral indices, although see below) on 1999 April 12, 16, 18 and 23, with the VLA in D-array. Data were reduced in the standard manner using the AIPS package. The resolution and baseline coverage of the VLA in D-array at 3.6 cm is close to that of the 20 cm FIRST data; thus extended emission might be detectable in the D-array 20cm maps that was missing in the 3.6cm maps. For sources with significant extended emission evident from the FIRST maps or from the D-array fluxes we assumed the extended emission had a radio spectral index $\alpha_{\mathrm{r}} = 0.75$ (defined such that flux density $S_\nu \propto \nu^{-\alpha_{\mathrm{r}}}$). We then calculated the integrated spectral index using the total (D-array) flux at 20cm and the sum of the peak and estimated extended flux at 3.6cm.

Fig. 1 shows the optical-luminosity – radio-luminosity plane for the FBQS quasars, together with $z < 0.5$ quasars from the PG sample [whose Hβ FWHM were measured by Boroson & Green (1992)]. The PG quasars are selected at a brighter optical flux limit than the FBQS quasars ($B \lesssim 16$), but as many of them are at $z < 0.3$ there is a reasonable overlap in optical luminosity between the two samples. As expected, the FBQS objects fill in the region between the radio-loud PG quasars (with radio luminosities at 5GHz, $L_{5\mathrm{GHz}} \gtrsim 10^{24.5}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$) and the radio-quiet PG quasars (with $L_{5\mathrm{GHz}} \lesssim 10^{23}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$) [5].

The samples have been divided into steep spectrum ($\alpha_{\mathrm{r}} \geq 0.5$) and flat spectrum ($\alpha_{\mathrm{r}} < 0.5$) subsamples (for some radio-faint PG quasars no ra-

[5]These divisions between radio-loud, radio-quiet and radio intermediate quasars are used throughout this paper.

dio spectral index information was available; they have been assumed to have $\alpha_r = 0.6$).

To measure the FWHM of Hβ we first subtracted the continuum and, where necessary, an FeII profile (Boroson & Green 1992) and [OIII]4959+5007 emission. As the quality of the spectra varied widely, FWHM were estimated by averaging those obtained from fits of Gaussian and Lorentzian profiles. This procedure was adopted as, where the signal-to-noise was high enough to make direct measurements of the FWHM, they typically lay between the values from Gaussian and Lorentzian fits. The error in a typical measurement is $\approx 10\%$, which translates to an $\approx 20\%$ error in black hole mass. We made a small correction to allow for the orientation dependence of FWHM Hβ (e.g. Brotherton 1996) by a factor of $R_c^{0.1}$, where R_c is the ratio of core to extended radio fluxes (where R_c could not be measured we assumed $R_c = 0.1$ for steep-spectrum sources and $R_c = 10$ for flat-spectrum ones).

3. Results

We derive black hole masses ($M_{\rm bh}$) following the prescription of Laor (1998), but use the recent empirical determination of the broad-line region radius from Kaspi et al. (2000). We plot them against radio luminosity in Fig. 2. The correlation of black hole mass with radio luminosity suggested by the work of Franceschini, Vercellone & Fabian (1998) and Laor (2000) is clearly present in the data. For the FBQS objects *alone* the Spearman rank correlation coefficient is 0.52 for the 60 objects in the sample, with a probability that no correlation is present of 0.01%, taking the 34 steep spectrum objects only this is 0.48 with a probability of no correlation of 0.6%. When the PG quasars are included the correlation becomes stronger still.

The FBQS objects fill in the gap between the radio-loud and radio-quiet objects in Fig. 1 of Laor (2000), providing evidence of a continuous dependence of radio luminosity on black hole mass. This suggests that selection effects, rather than underlying physics, could be responsible for producing the radio-quiet – radio-loud quasar dichotomy seen in some optically-selected samples (e.g. the PG sample). We speculate that the selection methods used for the FBQS have highlighted the radio-intermediate population, which for some reason is not so common in samples selected purely on the basis of radiative luminosity from the accretion disk. These issues will be discussed further in a future paper (Brotherton et al. 2001). We merely comment here that the FBQS is complete for radio-loud and radio-intermediate quasars, thus the ratio of radio-loud to radio-intermediate quasars in the FBQS should be representative of that of the quasar population as a whole.

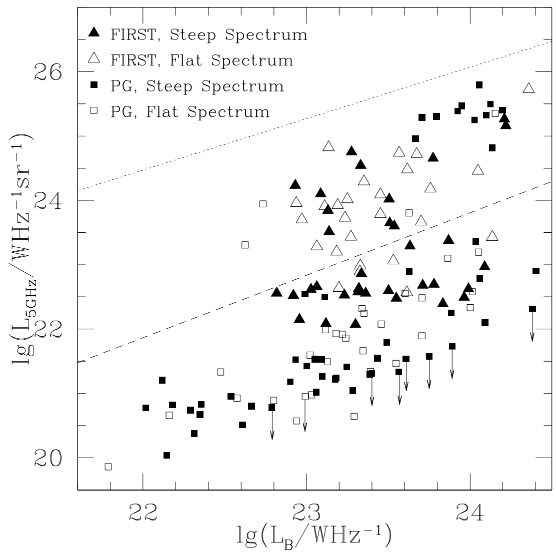

Fig. 1.— The radio-luminosity – optical luminosity plane for the samples of quasars discussed in the text. The dotted line is the radio-optical correlation for radio-bright quasars from the MRC sample (Serjeant et al. 1998). The dashed line corresponds to a radio-loudness parameter of $R^* = 10$, the traditional division between radio-loud and radio-quiet objects.

We also plot some galaxies with independent black hole mass estimates: three FRI galaxies with detected optical nuclei, M 84, M 87 and NGC 6251, whose black hole masses have been measured through the kinematics of their nuclear gas disks (e.g. Ferrarase & Ford 1999), three objects with low-mass black holes from the sample of Ho (1996) (including NGC 4258, whose black hole mass has been accurately measured using maser emission), and Sgr A*, the source at the Galac-

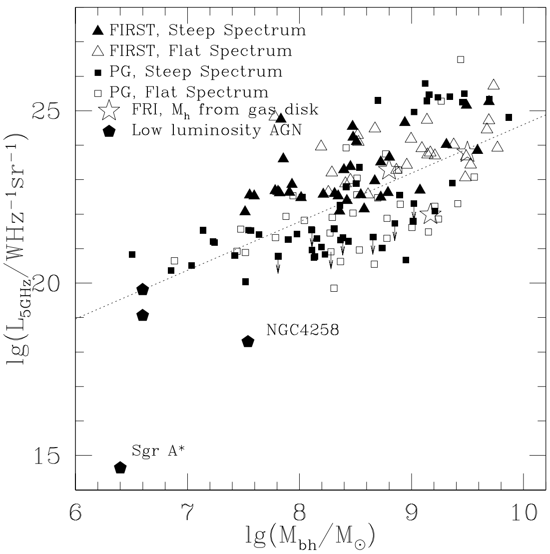

Fig. 2.— Radio luminosity versus black hole mass. The dotted line is the best fit to the correlation measured using the PG and FBQS quasars.

tic Center [using data from Falcke & Biermann (1999)]. The slope of the correlation of lg$L_{5\mathrm{GHz}}$ against lgM_{bh} measured for the steep spectrum quasars only using the EMMETHOD task in IRAF (Isobe, Feigelson & Nelson 1986), which takes into account limits in some of the data, is 1.4 ± 0.2. As expected, the flat-spectrum objects in each sample generally plot above the steep spectrum objects, but the mean enhancement due to Doppler boosting is, on average, not large (only $\approx$ 60% in the FBQS sample). It is possible that radio emission from star-formation processes could add significantly to the radio luminosities, particularly for the low radio-luminosity objects, which would tend to make our estimate of the slope low. However, Miller, Rawlings & Saunders (1993) argue that most of the radio emission in most PG quasars is related to the AGN.

Fig. 3 shows the correlation of the radio-loudness parameter, R^*, the ratio of rest-frame radio and optical luminosities as defined by Sramek & Weedman (1980), with M_{bh}. A Spearman correlation analysis [modified for use with data containing limits (Isobe et al. 1986)] using the steep spectrum objects only shows that the probability of this correlation arising by chance is $\sim 10^{-4}$.

4. Interpretation

Laor (2000) has suggested that quasars can be characterised by three parameters, namely black hole mass, the ratio of bolometric luminosity to the Eddington luminosity L/L_{Edd}, and orientation. By excluding the flat-spectrum quasars from our analysis and utilising the R_{c} – FWHM Hβ correlation we have eliminated orientation as a significant variable, leaving just M_{bh} and L/L_{Edd}.

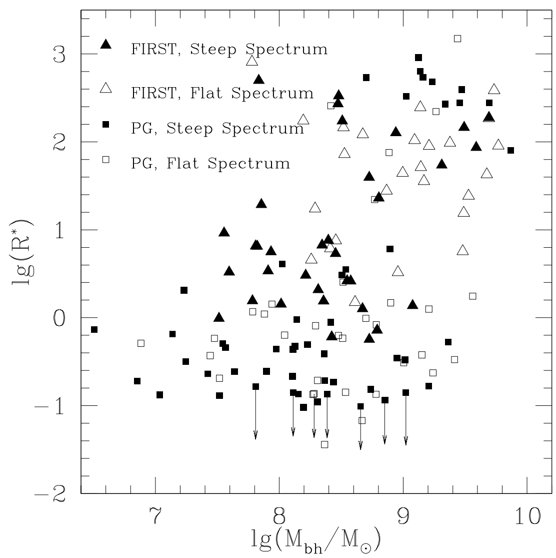

Fig. 3.— Radio-loudness parameter, R^*, against black hole mass

To disentangle these dependences, we fitted an equation of the form:

$$\mathrm{lg}L_{5\mathrm{GHz}} = a\,\mathrm{lg}w + b\,\mathrm{lg}L_B + c$$

to the data for the steep-spectrum PG and FBQS quasars using least-squares, where w is the velocity FWHM of Hβ. (For objects with only limits on their radio luminosity we set the radio luminosity equal to the limit.) By writing the derived quantities M_{bh} and L/L_{Edd} in terms of the observables w and L_{B} and the best-fit values of a and b we obtained the following empirical relation for the radio luminosity:

$$\mathrm{lg}L_{5\mathrm{GHz}} = 1.9\,\mathrm{lg}M_{\mathrm{bh}} + 1.0\,\mathrm{lg}(L/L_{\mathrm{Edd}}) + 7.9\,.$$

Corroborating evidence for an accretion rate dependence comes from studies of the correlation

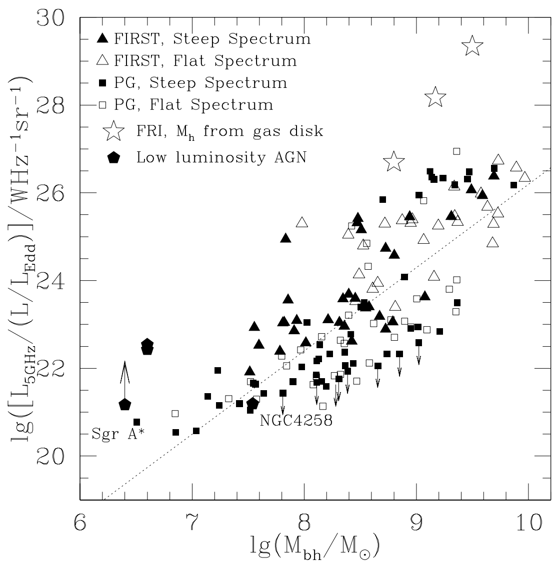

Fig. 4.— Radio luminosity divided by $L/L_{\rm Edd}$ (to account approximately for the accretion-rate dependence of radio-luminosity), against black hole mass. The dotted line is the best fit to the PG and FBQS quasars.

of radio and optical (continuum and/or emission line) luminosity for radio-selected AGN. As Fig. 2 shows, the range in black hole masses for radio-loud objects is very small. Thus the correlation of quasar optical luminosity with radio luminosity for quasars selected on the basis of bright radio emission (e.g. Serjeant et al. 1998), must be predominately a correlation of $L/L_{\rm Edd}$ with radio luminosity (Willott et al. 1999). Zirbel & Baum (1995) measure the logarithmic slope of this correlation to be 0.28 for FRI sources and 0.75 for FRII sources, and Jarvis et al. (2000) measure an even steeper slope for luminous high redshift FRII radio sources, close to our estimate of 1.0.

In Fig. 4 we plot $L_{\rm 5GHz}/(L/L_{\rm Edd})$ versus $M_{\rm bh}$. The correlation is indeed marginally tighter than that in Fig. 2; the Spearman rank correlation coefficient for the steep spectrum objects in Fig. 4 is 0.74, compared to 0.59 in Fig. 2. The slope of the correlation, as measured using EMMETHOD, is 1.9 ± 0.2 (although the slope appears to steepen towards higher $M_{\rm bh}$, we have not attempted a more complicated fit due to the large scatter and uncertainty over starburst contributions at low $L_{\rm 5GHz}$). The fact that the FRI sources and SgrA* plot above the correlation in Fig. 4 suggests that the accretion rate dependence of radio luminosity may weaken at the $L/L_{\rm Edd} \sim 10^{-5}$ accretion rates typical of FRI radio sources, consistent with the smaller logarithmic slope of the radio-optical correlation seen for FRI sources. Instead of reflecting a change in accretion-rate dependence, however, this weakening may alternatively be explained by a decrease in radiative efficiency of these systems at low accretion rates, as predicted by models of advection-dominated accretion flows (e.g. Narayan 1996), which would lead us to underestimate the true accretion rate. The $M_{\rm bh}$ dependence is similar to that found by Franceschini et al. (1998) for the much less luminous radio sources in nearby galaxy nuclei ($L_{\rm 5GHz} \propto M_{\rm bh}^{2.5}$). The difference in slope and normalisation to the quasar $L_{\rm 5GHz} - M_{\rm bh}$ relation noted by Laor (2000) is probably explicable in terms of lower accretion rates, and a different dependence of $L/L_{\rm Edd}$ on $M_{\rm bh}$ in these objects.

5. Comparison with models

Energy in the form of magnetohydrodynamic winds and/or a Poynting flux can, in principle, be extracted from either spinning black holes (Blandford & Znajek 1977) or accretion disks (e.g. Blandford & Payne 1982). Both the black hole and disk model predictions for the power output, $L_{\rm w}$, take a similar form, scaling with the square of the black hole radius (i.e. with $M_{\rm bh}^2$, for a Schwartzschild black hole), multiplied by the poloidal magnetic field in the inner disk/black hole region, B_p, squared (e.g. Livio, Ogilvie & Pringle 1999).

A full model for B_p does not currently exist, though equipartition assumptions suggest $B_p^2 \propto 1/M_{\rm bh}$ (e.g. Ghosh & Abramowitz 1997), implying $L_{\rm w} \propto M_{\rm bh}$. The accretion rate dependence probably arises through its influence on B_p. The models of Ghosh & Abramowitz (1997) do not predict a strong accretion-rate dependence at $L/L_{\rm Edd} \sim 0.1$, typical for our quasars, but those of Meier (2001) do.

Another possible source of non-linearity in the $L_{\rm 5GHz} - M_{\rm bh}$ relation arises from the conversion of radio jet power, Q (assumed $\propto L_{\rm w}$) to radio luminosity in the extended lobes of the ra-

dio source. If the minimum energy assumption is valid, $L_{5\rm GHz} \propto Q^x$, where $1.2 < x < 1.75$, depending on the radio source model (Miller et al. 1993). The case of $x = 1.75$ corresponds to a radio source in pressure balance with its external medium, whereas a purely ram-pressure confined, supersonically-expanding FRII radio source has $x \approx 1.2$. Models appropriate to the low-luminosity radio sources of radio-quiet and radio-intermediate quasars have yet to be published, but even so it seems hard to reproduce the observed $M_{\rm bh}$ dependence solely by this mechanism.

Are other conditions required to produce powerful radio jets? The standard deviation in $L_{5\rm GHz}/(L/L_{\rm Edd})$ about the best-fit line in Fig. 4 is 1.1 dex, about what one would expect given the ≈ 0.5 dex accuracy of black hole mass estimates from Hβ widths (Laor 1998), and the value of the slope. Therefore from our study alone there is no compelling statistical evidence for an additional factor being necessary to produce radio jets. However, the large scatter may well be hiding contributions from physically important effects, such as black hole spin and radio source environment. A related question is whether there are any actively accreting high mass black holes with very low radio luminosities in Fig. 4. This is best addressed using the PG quasars, whose selection criteria are radio-independent. There does indeed appear to be a genuine deficiency (Laor 2000), suggesting that the other variables affect radio luminosity by a factor of $\lesssim 1000$.

6. Summary

A plot of black hole mass versus radio luminosity for quasars from the FBQS and PG sample shows a continuous variation of radio luminosity with black hole mass for radio luminosities ranging from the traditional radio-quiet to radio-loud. Fitting the data for both a black hole mass and accretion-rate dependence, we find that radio luminosity scales approximately as:

$$L_{5\rm GHz} \propto M_{\rm bh}^{1.9\pm0.2} (L/L_{\rm Edd})^{1.0}$$

at accretion rates of $L/L_{\rm Edd} \sim 0.1$. At lower accretion rates, we suggest an apparent weakening of the accretion rate dependence, to $L_{5\rm GHz} \propto (L/L_{\rm Edd})^{0.3}$ at $L/L_{\rm Edd} \sim 10^{-5}$ (or a corresponding decrease in the radiative efficiency). The radio and optical luminosity of quasars have quite different dependences on $M_{\rm bh}$, which may explain why the radio luminosity distribution of quasar surveys differ so dramatically depending on whether or not selection is based on detection in the radio.

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